Mechanical damping of wood as related to species classification: a preliminary survey

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Abstract

Some morphological and biochemical taxonomic markers are also affecting factors of dynamic mechanical properties of wood. Thus, could these properties reflect the classification/phylogeny of taxa? This work is a first insight into this question. It relied on the gathering (through experimental campaigns and exhaustive literature review) of a large database on the viscoelastic (i.e. including damping) vibrational properties of 445 woody species. The "standard" relationship between damping coefficient (tanδ) and specific modulus of elasticity (E'/ρ) was confirmed at a wide interspecific scale, but described no more than 40% of tanδ variations. Damping and E'/ρ fluctuated between families, yet not in a way that could be easily related to the phylogenetic tree. Damping was a bit more discriminating than E'/ρ. Some families had nearly systematically lower (Fabaceae-Papilionoideae and, to a lesser extent, Lauraceae, Cupressaceae and Moraceae) damping than average, independently of E'/ρ. On the contrary, Fagaceae, Betulaceae and Sapindaceae had higher damping than average. While for some other families no clear characteristics could be observed – at least with the present number of represented species. In the future, increasing the amount of data and compiling anatomical and chemical markers / affecting factors will allow further analysis at sub-family levels, and a better understanding of this wide topic.

Introduction

Dynamic mechanical properties of wood in given conditions of time-frequencies, temperature and moisture content are related to superimposed effects of the organization and orientation of wood elements (cells and microfibrils) and of characteristics of chemical composition [1,2]. Such affecting factors may in turn be morphological and biochemical markers of the botanical classification or phylogeny of woody species. The usefulness of wood anatomy in systematic studies has been long recognized. Criteria such as the proportion of different types of cells / tissues and cell-wall thickness affect specific gravity. Yet little is currently known about any potential dependence on classification of parameters such as microfibril angle and grain deviation which are known to affect axial mechanical properties. On the other hand, different taxa can have different "enzymatic machineries" regulating their biosynthetic pathways. Especially, secondary metabolites are extremely diverse and their nature depends on families, genus or species (c.f. chemotaxonomic studies). They are also expected to play a significant, and probably compound-dependant, role in modulating mechanical damping [3,4,5,6].

Given these considerations, we expect that some of the wood morphological and biochemical diversity would be reflected in their mechanical behaviour. This work is a first insight into the potential categorization of taxa depending on their dynamic mechanical properties. Though, considering actual biodiversity, little information is currently available about inter-specific variability of mechanical damping. The prerequisite for our analyses thus relied on the gathering of a large collection of information on the viscoelastic (i.e. including damping) vibrational properties of woody species [7]. In this paper, preliminary analyses are made at the botanical family level.

Methodology

Experimental characterizations

Characterizations of vibrational properties in axial direction were performed on 76 wood species. About 2 thirds of the material has been obtained from well-identified stocks from CIRAD, Montpellier. The remaining part was obtained from various sources and, when necessary, subsequently identified. The total sampling covered more than 1300 specimens.

Specimens (12×2×150mm, R×T×L) were first dried (in order to reach equilibrium in adsorption) for 48h at 60°C. After at least 3 weeks stabilization in controlled conditions of 20±1°C and 65±2%RH, vibrational measurements were performed by non-contact forced vibrations of free-free bars (see *Fig. 1*), e.g. [1,8]. Specimens were suspended by thin silk threads located at the nodes of vibration for the first mode. They were made to vibrate through an electro-magnet facing a thin iron plate glued on one end of specimens. Displacement was measured by a laser triangulation sensor. A frequency scanning allowed determining the resonance frequency and its bandwidth. Then excitation was set at the resonance frequency, then cut off and the decrement of amplitude was recorded. E'/ρ was deduced from the first resonant frequency according to the Euler-Bernouilli equation. Damping or loss coefficient –expressed as $\tan\delta$- was measured both through the 'quality factor' Q (bandwidth at half-power; frequency domain) and through logarithmic decrement λ of amplitude after stopping the excitation (time domain). Measurement frequencies were in the range of 200-600 Hz. 3 repetitions were made for each probe and mean error on properties was ≤5%.

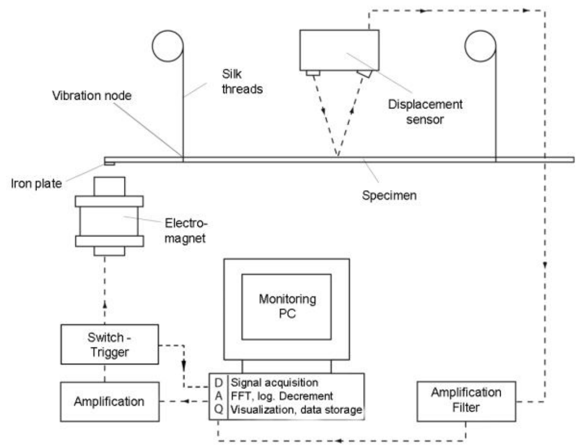


Fig. 1 Schematic drawing of the apparatus for non-contact forced vibrations of free-free slender beams.

Data compilation

Data obtained through our experimental characterizations were much extended by an extensive literature review on wood viscoelastic (i.e. data including damping coefficients) vibrational properties. Data were collected from 30 sources, including some hard-to-obtain ones. Great care has been taken about checking the compatibility of all collected values, especially considering the hygrothermic and frequency conditions of measurements. The data compiled were obtained on woods stabilized in controlled conditions of 20-25°C, at c.65% RH (55-70% RH were accepted but specified) and in the frequency range of 200-1500Hz (data at higher frequencies are listed separately). Basic set of properties includes specific gravity (ρ), Young's modulus (E), specific dynamic Young's modulus (E'/ρ) and damping coefficient ($\tan\delta$), along the grain (some information on anisotropy ratios were also collected). This "wood vibrational properties" collection contains data for 445 woody species (corresponding to the results of 6000 tests), including 65 gymnosperms (/softwoods), 8 monocotyledons and 377 dicotyledons angiosperms (with 268 tropical, and 104 temperate hardwoods). The nomenclature of species was checked in order to assign them up-to date valid botanical name. Their classification was recorded both in the classical system and in the phylogenetic one according to the APG (Angiosperm Phylogeny Group, [9]) families and orders. The 445 compiled species belonged to 237 genera from 69 APG families.

Results and discussion

Properties distribution and relations

Across the 445 compiled species, damping coefficient (tanδ) ranged from 3.7 to 20 ‰. Its variations were roughly related (see *Fig 2*) to specific modulus of elasticity (E'/ρ) in a way very similar to the "standard" relationship established by Ono and Norimoto [10,11]. Though, this relation described less than 40% of actual variations in tanδ. However, in order to compare specifically the damping characteristics of taxa, it is necessary to de-correlate them from E'/ρ. This could be achieved by using two indicators: the specific loss modulus (E''/ρ) which is a mechanical property in itself (equation 1) or the deviation from standard damping (Δtanδ), a simple statistical indicator defined in equations (2) and (3), where $\tan\delta_S$ is the standard trend reported by [10].

$$E \quad \rho = \quad \times \quad \rho) \qquad (1)$$

$$\Delta \quad = \quad \times \frac{\tan\delta_t - \quad \delta_s}{\tan\delta_s} \qquad (2) \text{ with: } \tan\delta_s = \quad \times \quad \rho)^{-0.68} \qquad (3)$$

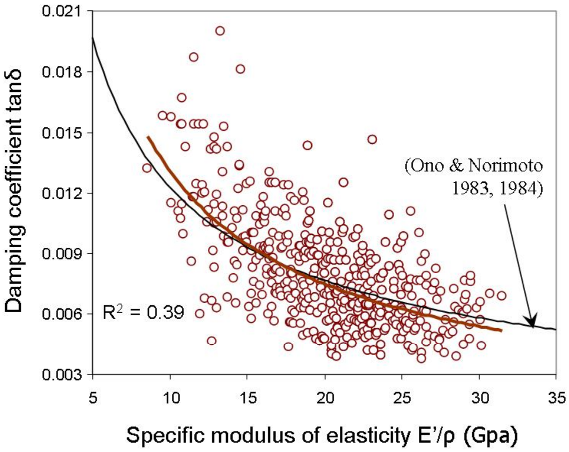


Fig. 2 Relationship between damping coefficient and dynamic specific modulus of elasticity. Each point is the mean of one species, N=445.

The collected set of species sounded quite representative, as the mean values (see *Table 1*) of specific gravity (ρ) and of E'/ρ across the 445 studied species are very close to those reported on bigger numbers of species: 0.73 for the mean specific gravity of 3805 species [12], 21.7 for the mean E'/ρ of 870 species [13]. Variations in specific modulus and damping coefficient were not related to those in specific gravity. Concerning characteristic damping indicators, "normalized damping" (Δtanδ) much better explained actual damping coefficient than E''/ρ did, thus, further analyses will make use of this indicator.

Table 1 Basic statistics of dynamic mechanical properties and specific gravity across the 445 studied species: Pearson's correlation coefficients between properties (top rows), and mean values and range (bottom rows).

N=445	ρ	E'/ρ	tanδ	Δtanδ	E''/ρ
ρ	1				
E'/ρ	0.00	1			
tanδ	-0.19	-0.62	1		
Δtanδ	-0.26	-0.12	0.83	1	
E"/ρ	-0.26	0.20	0.60	0.95	1
		(GPa)	(‰)	(%)	(Mpa)
mean	0.72	20.1	8.1	+1	154
min	0.18	8.6	3.7	-55	59
max	1.33	31.5	20.0	+97	284

Properties variations between botanical families

Across 20 APG families represented by at least 5 species (from at least 3 genera), the mean values and the ranges of variations in normalized damping, and in specific Young's modulus, clearly fluctuated (see *Fig. 3*). Though, the ranges most often overlapped between families, and the fluctuations in mechanical properties did not appear to be easily linked to evolutionary patterns as roughly described by an arrangement according to the APG phylogeny tree – at least at the family level and with the present number of represented species. Yet, some families (or sub-families) had nearly systematically lower (e.g. Fabaceae-Papilionoideae, Lauraceae) or higher (e.g. Betulaceae, Sapindaceae) damping than average. Few families had ranges in E'/ρ clearly departing from the global mean value. However, discrepancies in sample size make it difficult to check out the significance of any apparent differences. In this scope, we further isolated 13 families represented by at least 10 species belonging to at least 3 genera (see *Fig. 4*).

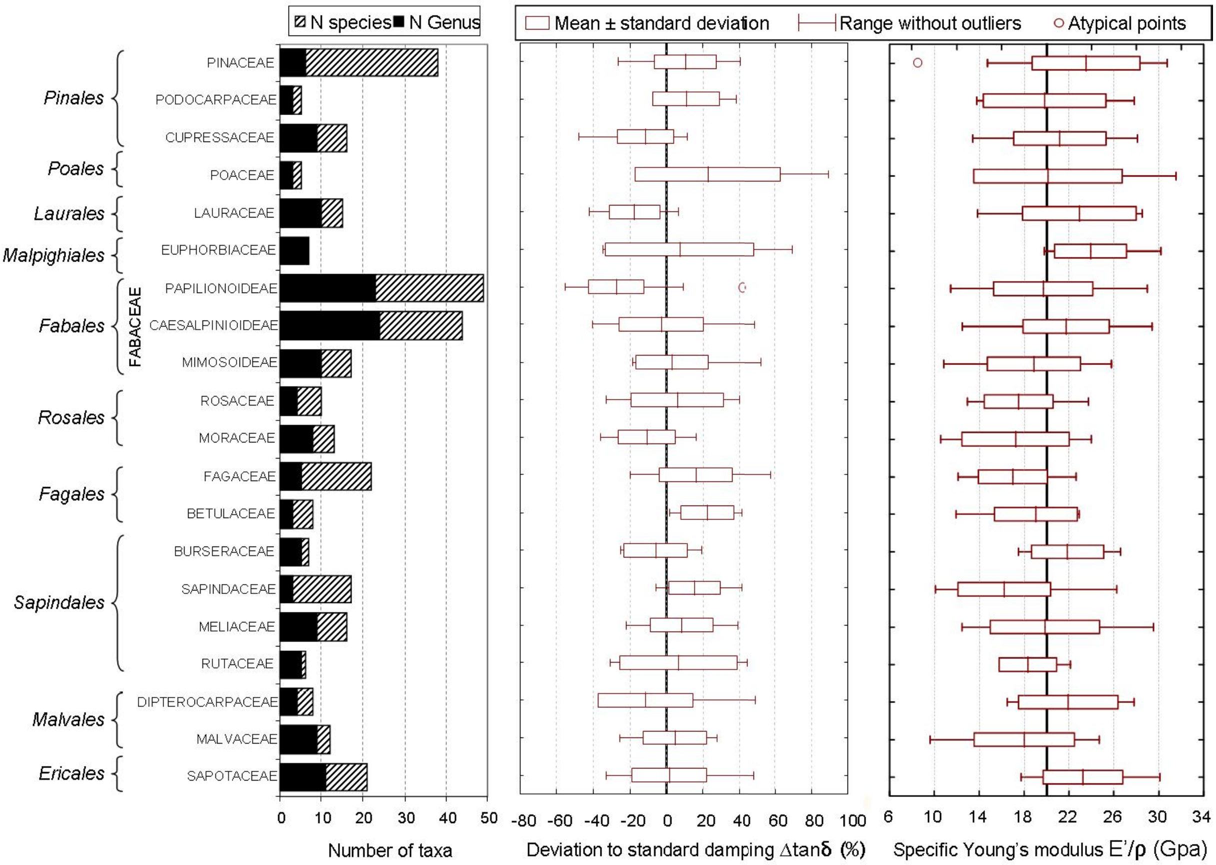
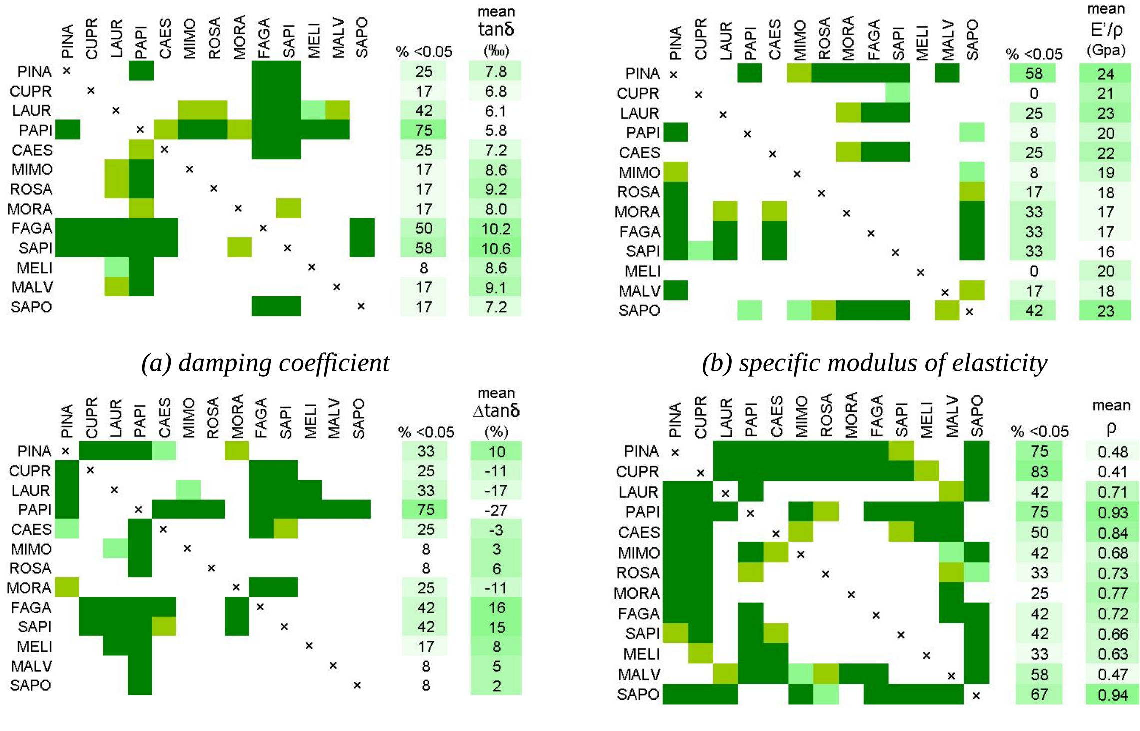


Fig. 3 Ranges of variations in normalized damping Δtanδ and in specific modulus of elasticity E'/ρ for 20 APG families represented by at least 5 species from at least 3 genera. Families are roughly arranged vertically according to phylogenetic trees from [APG] . Bold lines represent the mean value of Δtanδ and of E'/ρ on 445 species.

Some families had significantly different damping coefficient (*Fig. 4a*) from several others: Fabaceae-Papilionoideae had a lower tanδ than ¾ of other studied families, Lauraceae followed a similar trend but with less numerous significant differences. In contrast, Sapindaceae and Fagaceae had significantly higher tanδ than at least half of other families. These trends must be compared with specific modulus of elasticity (*Fig. 4b*): Fab-Papilionoideae were here not different from the mean, while Fagaceae and Sapindaceae had the lowest E'/ρ (statistically different from one third of other families). There were less numerous significant differences between families in E'/ρ than in tanδ. Pinaceae were the most clearly different in terms of higher E'/ρ (followed by, in a lesser extent, Sapotaceae and Lauraceae). As a result, although tanδ of Pinaceae was within the global average, it was in fact significantly higher than standard (*Fig. 4c*), while the low tanδ of Lauraceae resulted both from a high E'/ρ and from an intrinsically lower "viscosity". On the other hand, the high damping coefficient of Sapindaceae and Fagaceae resulted not only from their low E'/ρ but also from a significantly more viscous nature than usual. The sub-familly Papilionoideae was an interesting case as its specific modulus of elasticity was strictly within average, while having the lowest and most atypical damping, independently of E'/ρ. It is also interesting to note the differences between the sub-families Papilionoideae and Caesalpinioideae, although the latter contains some species with notoriously low damping due to secondary metabolites [4], but its range extends from very low to quite high tanδ and Δtanδ. Maybe the common presence [9] of secondary metabolites from the isoflavonoids group in the Papilionoideae would be of significance concerning their very low damping? Incidentaly, the inclusion of the tribe Swartziae (which had been formerly described as basal between the two sub-famillies [14]) in the Papilionoideae rather than in the Caesalpinoideae plays a clear role in the observed differences between them. This also suggests that further analysis at sub-family levels (tribes, genera, when enough data are available) could bring more detailed understanding of the observed differences.



(a) damping coefficient *(b) specific modulus of elasticity*

(c) deviation to standard damping *(d) specific gravity*

■*probability≤ 0.01* ■*0.01<probability≤ 0.05* ■*0.05<probability≤ 0.1*

Fig. 4 One-to-one significance of differences in properties between 13 families represented by at least 10 species from at least 3 genera. ANOVA with Post-Hoc HSD Tuckey test.

Finally, specific gravity (*Fig. 4d*) better discriminated families overall, but when considering only angiosperms, damping offered nearly as good distinctions. Yet, comparison of the scheme for dynamic mechanical properties and for specific gravity shows that differences between families follow different patterns depending on wood properties, presumably reflecting different levels of morphological and biochemical markers. Specific gravity basically reflects cellular organization (i.e. cell-walls to void ratios) with possible additional contribution of incrusted secondary metabolites (e.g. for several Papilionoideae, here). E'/ρ should result principally from cell-wall elastic properties (with strong influence of microfibril angles) but also to some aspects of cellular and tissue arrangement (ratios of fibres to other cellular types, fibres deviations/patterned grain). Δtanδ should mostly reflect variations in chemical composition able to modify viscous behaviour. Thus, further steps for extending the present analysis should involve the compilation of such morphological and biochemical markers in order to interrelate them with dynamic mechanical properties.

Conclusion

This work was a first insight into the possible relations between species classification and wood dynamic mechanical properties, relying on an extensive data compilation on these properties. First analyses revealed that:

- The "standard" relation reported in the literature between damping coefficient (tanδ) and specific modulus of elasticity (E'/ρ) was corroborated at interspecific level on a large scale, but explained less than 40% of actual variations.
- Ranges in dynamic mechanical properties fluctuated between botanical families, but trends were not directly linked to phylogenetic trees at this level. Families were apparently better discriminated according to damping than to E'/ρ.
- Some families had nearly systematically lower intrinsic damping than average: Fabaceae-Papilionoideae, and in a lesser extent Lauraceae, Cupressaceae and Moraceae.
- On the contrary, Fagaceae, Betulaceae and Sapindaceae had higher damping than average. Despite their higher E'/ρ, Pinaceae also tended to have higher damping than standard.

Our results confirmed that dynamic mechanical properties are probably affected by some morphological and/or biochemical taxonomic markers. Further analyses should thus involve data compilation of such markers in order to interrelate them to properties. Analyses at sub-family levels should also prove useful in better describing the repercussion of biodiversity on wood properties.

Acknowledgements

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